Status of High latitude precipitation estimates from observations and reanalyses

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Key points:

1- ERA- Interim and MERRA agree closely with CloudSat precipitation over high-latitude oceans.
2- Over Antarctica total snowfall from GPCP and CloudSat is almost identical: about 178 mm/yr.
3- GPCP likely overestimates snowfall over Eurasia.

Abstract

An intercomparison of high-latitude precipitation characteristics from observation-based and reanalysis products is performed. In particular the precipitation products from CloudSat provide an independent assessment to other widely used products, these being the observationally-based GPCP, GPCC and CMAP products and the ERA-Interim, MERRA and NCEP-DOE R2 reanalyses. Seasonal and annual total precipitation in both hemispheres poleward of 55° latitude is considered in all products, and CloudSat is used to assess intensity and frequency of precipitation occurrence by phase, defined as rain, snow or mixed phase. Furthermore, an independent estimate of snow accumulation during the cold season was calculated from the Gravity Recovery and Climate Experiment (GRACE). The intercomparison is performed for the 2007-2010 period when CloudSat was fully operational. It is found that ERA- Interim and MERRA are broadly similar, agreeing more closely with CloudSat over oceans. ERA-Interim also agrees well with CloudSat estimates of snowfall over Antarctica where total snowfall from GPCP and CloudSat is almost identical. A number of disagreements on regional or seasonal scales are identified: CMAP reports much lower ocean precipitation relative to other products, NCEP-DOE R2 reports much higher summer precipitation over northern hemisphere land, GPCP reports much higher snowfall over Eurasia, and CloudSat overestimates precipitation over Greenland, likely due to mischaracterization of rain and mixed-phase precipitation. These outliers are likely unrealistic for these specific regions and time periods. These estimates from observations and reanalyses provide useful insights for diagnostic assessment of precipitation products in high latitudes, quantifying

the current uncertainties, improving the products, and establishing a benchmark for assessment of climate models.

1. Introduction

Precipitation characteristics are expected to change in a warming climate [Trenberth 2003; Stephens et al., 2008]. Accurate quantification of the amount and distribution of precipitation is critical to understanding the current state of Earth's climate and water and energy budget [Stephens et al., 2012; Trenberth et al., 2007; Rodell et al., 2015; L'Ecuyer et al., 2015], and how the hydrological cycle responds to the energy imbalances that force climate change [Andrews et al., 2009]. Changes in the amount, frequency, and intensity of precipitation can significantly impact regional hydrologic processes and may have severe impacts on socioeconomic sectors and agricultural productivity.

High-latitude regions respond more strongly to anthropogenic climate change than other regions according to surface temperature observations and climate model simulations [Serreze and Francis, 2006; Solomon et al., 2007], and an intensification of high-latitude precipitation is also projected by climate models [Lau et al., 2013]. Reported changes in high-latitude hydrology have been inferred from changes in snow cover, mountain glacier area, permafrost extent and lake area [Smith et al., 2005; Alley et al. 2007], and increasing freshwater discharge [Yang et al., 2002; Dyurgerov and Carter, 2004; McClelland et al., 2006]. Reduced uncertainty in precipitation estimates is required to fully contextualize these changes, understand physical processes, and

46 reliably detect and quantify possible changes in the high-latitude hydrological cycle [Ye

47 et al., 2014].

48

49 Climate models are known to contain large biases in precipitation [Stephens et al., 2010]

50 and observational precipitation products contain large uncertainties [Behrangi et al.,

51 2012] particularly where ground measurements are sparse, such as over the oceans and

52 high-latitude regions [Adler et al., 2012]. It is therefore essential to characterize and

53 utilize other observation sources to quantify high-latitude precipitation. This is

54 especially important as the number of precipitation gauges at northern high latitudes

55 has sharply decreased since 1990 [Serreze et al., 2005] and only a handful of gauges are

56 operating in Antarctica. Furthermore, existing gauges often face large biases caused by a

57 number of factors such as wind-induced undercatch [Goodison et al., 1998], particularly

58 for snow, where correction factors can lead to uncertainties of order 100% [Yang et al.,

59 2005; Fuchs et al., 2001].

60

61 Given the importance and challenge of quantifying high-latitude precipitation, the

62 present study investigates high-latitude precipitation from products that are often used

63 in climate analysis and assessments of climate models. Furthermore, newly emerged

64 capabilities for quantification of high-latitude precipitation with the CloudSat Cloud

65 Profiling Radar (CPR)[Stephens et al., 2008] and the Gravity Recovery and Climate

66 Experiment (GRACE)[Tapley et al., 2004] are exploited to provide independent

67 precipitation or accumulation estimates.

68

69   CloudSat provides direct observations of snow and light rainfall at high latitudes with

70   unprecedented signal sensitivity (e.g., minimum detectable signal of ~-28 dBZ) but, it

71   suffers from occasional signal saturation which we ameliorate here by referring to the

72   Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E). CloudSat

73   provides a rain product that is optimized for use over the oceans where no gauges are

74   available, and a snow product that is designed to work over both land and ocean, and

75   which is not vulnerable to the large uncertainties introduced by gauge undercatch of

76   snow in windy conditions. Another instrument that has shown highly useful for

77   measuring total snow accumulation [Landerer et al., 2010; Swenson, 2010] is NASA's

78   Gravity Recovery And Climate Experiment (GRACE) satellite mission. GRACE provides

79   monthly observations of changes in the Earth's gravity field and is well suited for

80   measuring changes in continental-scale water storage. To our knowledge this is the first

81   time that global high latitude precipitation is assessed using such various datasets.

82

83   Detailed information about the products, instruments and methods are provided in

84   Section 2. Section 3 reports and discusses the results of the intercomparison split by

85   region before Section 4 concludes.

86

87   **2. Data resources and methods**

88   Current precipitation products may be considered as belonging to one of four groups:

89   gauge-only, satellite-only, satellite and gauge, and reanalysis. Each product was

90   remapped onto a common 2.5°×2.5° lat-lon grid to match the lowest-resolution dataset,

91   avoiding issues with downscaling and ensuring sufficient CloudSat retrievals within each

92 grid cell. We remapped the products using linear spatial interpolation. While there are

93 numerous interpolation schemes available (e.g., Kriging, Linear, Natural Neighbor,

94 Nearest Neighbor, Polynomial Regression), we use linear interpolation as it makes very

95 little difference on the gridded quantity averages. These methods were applied to

96 CloudSat precipitation rates and found that the choice of the method resulted in a

97 maximum difference of 0.005% compared to the linear method. Intercomparison is

98 conducted for the period 2007 to 2010, during which both CloudSat and AMSR-E were

99 almost fully functional.

100

101 **2.1 Gauge product**

102 **2.1.1 GPCC**

103 The Global Precipitation Climatology Centre (GPCC) was established in 1989 at

104 Deutscher Wetterdienst under the World Meteorological Organization (WMO) as the in

105 situ component of the Global Precipitation Climatology Project (GPCP) of the Global

106 Energy and Water Exchanges (GEWEX) project. GPCC integrates data from various

107 networks, organizations, and additional precipitation data through bilateral contacts and

108 with the support of WMO to its database [Schneider et al., 2014] and thus employs more

109 gauges compared to other popular gauge products. However, in many regions --

110 especially at high latitudes-- gauges are sparse or non-existent. For example, only a

111 handful of gauges are operating over entire Antarctic and Greenland (Fig. 1). Therefore,

112 gauge-based estimates of precipitation in these regions have to rely on interpolation of

113 sparse data, reducing the quality of the product there.

114 Before merging the data from different sources, quality control and homogenization of

115 station metadata are performed, but the product does not include bias correction for

116 systematic gauge measuring errors. In this study we used GPCC Full Data Reanalysis

117 Version 7.0 at 2.5°×2.5° resolution. Details for construction of gridded precipitation

118 products and data access are described in Becker et al. (2013) and Schneider et al.

119 [2014; 2015].

120

121 **2.2. Satellite-gauge products**

122 **2.2.1 GPCP**

123 GPCP was formed as a community-based analysis of global precipitation under the

124 auspices of the World Climate Research Program (WCRP) and is being widely used by

125 the research community. GPCP is a merged product using data from gauges over land,

126 and from spaceborne sensors over both land and ocean including Special Sensor

127 Microwave Imager (SSMI), Special Sensor Microwave Imager/Sounder (SSMIS), and

128 geostationary and polar orbiting infrared imagers and sounders. Gauge-based estimates

129 are adjusted for gauge undercatch using climatological factors. In the high latitudes

130 (starting at $\sim$40°), precipitation (including snow) rate is obtained using a regression

131 relationship between historical collocated rain gauge measurements (adjusted for wind

132 loss, including relation to snow) and a few cloud-related parameters (e.g., cloud-top

133 pressure, fractional cloud cover, and cloud-layer relative humidity; Susskind et al.

134 [1997]). The cloud parameters are retrieved from Television Infrared Observation

135 Satellite (TIROS) Operational Vertical Sounder (TOVS) and Atmospheric Infrared

136 Sounder (AIRS).

137   The latest version of the monthly 2.5°×2.5° resolution GPCP product (version 2.2;

138   Huffman and Bolvin, [2012]) available from Goddard Earth Sciences Data and

139   Information Services Center (GES DISC) is used. Detailed description of the product can

140   be found in [Adler et al., 2003; Huffman et al., 2009; Huffman and Bolvin, 2012].

141

142   **2.2.2 CMAP**

143   The Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) product

144   [Xie and Arkin, 1997] is also widely used. CMAP provides gridded global monthly

145   estimate of precipitation at monthly 2.5°×2.5°resolution using many of the same

146   datasets as GPCP. It also uses precipitation data from Microwave Sounding Units (MSUs).

147   However, the merging of the individual data sources is different from GPCP. Unlike GPCP

148   it does not use AIRS/TOVS in high latitudes and makes no undercatch adjustment for

149   gauge measurements. Over land, the blended analysis is controlled by gauge

150   observations which capture snowfall, but over ocean the satellite estimates (IR and

151   PMW) implicitly include snowfall as they only estimate total precipitation and snow

152   remains to be difficult to retrieve. The product was obtained from the NOAA's Earth

153   System Laboratory via: http://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html.

154   Unlike GPCP, CMAP does not adjust gauge-based estimates for assumed undercatch.

155

156   **2.3. Satellite-only products**

157   **2.3.1. CloudSat**

158   The 94-GHz nadir-looking CPR on CloudSat provides unprecedented sensitivity to

159   retrieve snowfall and light rain. The CPR footprint is ~ 1.7 km along track and ~1.4 km

160 cross track. CloudSat precipitation data have been invaluable in advancing cold-region

161 and high-latitude precipitation analysis [Behrangi et al., 2012; 2014a,b; Palerme et al,

162 2014].

163

164 Three CloudSat products are used here: 2C-PRECIP-COLUMN R04 (henceforth "2c-

165 column"; Haynes et al. 2009), 2C-RAIN-PROFILE R04 (henceforth "2c-rain")[Lebsock and

166 L'Ecuyer, 2011] and 2C-SNOW-PROFILE (henceforth "2c-snow")[Wood et al., 2013 and

167 2014] along with the CloudSat auxiliary AMSR-E product CS_AMSRE-AUX (henceforth

168 "AMSR-E") generated by CloudSat team. All data are available at:

169 http://www.cloudsat.cira.colostate.edu.

170 The 2c-column product provides precipitation occurrence through flags representing

171 the phase (rain, snow or mixed) and likelihood of precipitation (certain, probable,

172 possible). The 2c-rain product then calculates rain rate when the flag is certain for rain

173 or mixed phase, while the 2c-snow product calculates snow also in snow possible cases

174 provided that the estimated melted fraction is under 0.1. For consistency we restrict our

175 analysis to "certain" for all phases. Where the flag is rain certain, the corresponding

176 intensity is extracted from 2c-rain, for snow certain the intensity is taken from 2c-snow,

177 and for mixed phase certain the mean value from 2c-snow and 2c-rain is used if both are

178 nonzero, otherwise the single nonzero value from 2c-snow or 2c-rain is used. This

179 occurs in few cases due to temperature or melted-fraction thresholds in the retrieval

180 algorithms.

181

182   In intense rain the radar signal is saturated and the CloudSat algorithm provides a lower

183   limit on the rain intensity, although some adjustments can be made to provide better

184   estimates of heavy precipitation [Stephens et al., 2010; Matrosov, 2014]. Here we choose

185   to make no adjustment and select the largest value out of this lower limit and the

186   coincident AMSR-E from CS_AMSRE-AUX. In the Southern Hemisphere poleward of 55°

187   latitude (SH55), 0.4% of rain events result in saturation, and in the Northern

188   Hemisphere poleward of 55° (NH55) 0.2% are saturated. Thus, while there is a potential

189   underestimate of precipitation rates in the most intense events, the size of this

190   underestimate should be limited by the rarity of these events and the inclusion of AMSR-

191   E retrievals.

192

193   Similarly, the exclusion of possible or probable precipitation events may lead to an

194   underestimate, although analysis of the 2c-snow product suggests that this is also small.

195   Non-certain events tend to be of low intensity and in the case of the 2c-snow product,

196   including non-certain snow events would only increase the mean snowfall rate in the

197   SH55 region by +2.9% and in the NH55 region by +4.5%.

198

199   There are further issues to consider regarding the CloudSat rain rate retrieval algorithm.

200   Firstly, it uses ocean reflectance properties in its path integrated attenuation approach

201   [Haynes et al., 2009]. Over land the surface reflectivity properties are not as well known,

202   resulting in uncertainty in the rain rate retrievals. The magnitude of any potential bias

203   has not yet been quantified. Secondly, when the surface topography is rough the CPR

204   may receive backscatter from ice or land surfaces at high altitudes, which it

misinterprets as being very intense near surface rain. The 2c-snow algorithm uses vertical reflectivity continuity tests to eliminate this scenario, but these tests have not been applied to the 2c-rain product to date. The above issues affect only the rain rates retrieved over land, and not the frequency of occurrence or snow rates. A relevant concern for all of the CloudSat retrievals is that it does not fully sample the diurnal cycle with overpasses occurring near 1:31 a.m. and 1:31 p.m. local time. We are unable to correct for this sampling issue and it remains an unquantified source of uncertainty. However, as shown in Behrangi et al. [2012] the effect is likely small over ocean.

2.3.2. GRACE

The Gravity Recovery and Climate Experiment (GRACE) data are used to calculate precipitation accumulation during the winter season over land. GRACE is a twin satellite mission that has measured range-rate variations between the two satellites using microwave interferometry since 2002. Gravity changes due to mass redistribution by solid-earth processes and hydrology perturb the GRACE orbit, allowing retrieval of mass variations with high accuracy [Tapley et al., 2004]. GRACE has been used extensively to study changes in terrestrial water stores (snow, ice, surface water, soil moisture, and groundwater [Niu et al., 2007; Swenson and Wahr, 2007; Swenson et al., 2006; Swenson et al., 2010; Landerer et al., 2010].

During winter, almost all land poleward of 55° latitude experiences near surface temperature below -2°C, and hence much of the precipitation falls as snow. Evapotranspiration and runoff are relatively small in winter [Serreze et al., 2003;

228   Lammers et al., 2001], such that, after accounting for solid earth processes, the gravity

229   anomaly measured by GRACE over high latitude regions at this time of year is primarily

230   due to the accumulated snowfall. A GRACE-based estimate of winter precipitation

231   accumulation is unique in that: (i) it is based on a completely independent technique

232   (gravimetry versus radiometry) with no need for empirical parameterizations, ground-

233   based calibration, or correction for gauge undercatch, (ii) it captures accumulated

234   precipitation so does not miss precipitation occurring between satellite overpasses, and

235   (iii) during wintertime, other satellites and ground measurements face the highest

236   uncertainty. Furthermore, the measurement noise of GRACE is smallest in high latitudes

237   because of GRACE's high density of orbits there.

238

239   Precipitation accumulation is calculated from GRACE Terrestrial Water Storage Anomaly

240   (TWSA) based on mass conservation [Dingman, 2008]. If t_1 is accumulation start-time

241   (e.g., early winter) and t_2 is the accumulation end-time (e.g., late winter) for domain D,

242   the water storage change between time t_1 and t_2 can be calculated as

243   $\quad S(t_2) - S(t_1) = \Delta P - \Delta ET - \Delta Q$ (Eq. 1)

244   Where S, P, ET, Q, represent water storage, precipitation, evapotranspiration, and

245   discharge for domain D, respectively and Δ represents the net change between t_1 and t_2.

246   ΔP is the accumulated precipitation during winter.

247

248   Over the Greenland and Antarctic ice sheets, the use of GRACE to estimate the

249   accumulated snowfall is complicated by ice divergence (continual export of mass from

250   the interior to the oceans via ice flow)[Rignot et al., 2011]. Therefore, the present study

251   does not include these regions in the analysis.

252

253   Monthly 1° x 1° gridded GRACE total water storage anomalies are obtained from the

254   latest release (RL 5) from Center for Space Research at University of Texas, Austin (CSR)

255   with corrections applied [Landerer and Swenson, 2012; Swenson and Wahr, 2006],

256   available at http://gracetellus.jpl.nasa.gov/. Sakumura et al. [2014] showed that using

257   an ensemble average of the gravity field solutions from CSR and two other processing

258   centers can reduce noise. However, differences between the three products are small

259   and fall within the error bounds of the GRACE solution itself. Evapotranspiration and

260   runoff are obtained from GLDAS Noah Land Surface Model L4 monthly 0.25 x 0.25

261   degree Version 2.0 (GLDAS_NOAH025_M) product [Rodell et al., 2004], available from

262   NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC). The

263   calculations are performed at 1° x 1° resolution and the results are mapped to the

264   common 2.5^o x 2.5^o resolution used for comparison

265

266   **2.4. Reanalysis products**

267   **2.4.1. ERA-interim**

268   ERA-interim [Dee et al., 2011; Simmons, 2014] is the latest European Center for

269   Medium-Range Weather Forecasting (ECMWF) global atmospheric reanalysis. ERA-

270   interim relies on a 4D-VAR (rather than 3D-Var as in ERA-40) system which uses

271   observations within 12-hour windows to initialize forecast simulations. This study uses

272   daily precipitation obtained from http://apps.ecmwf.int/datasets/ at 1.5° x 1.5° spatial

273   resolution.

274

275   **2.4.2. MERRA**

276   The Modern Era Retrospective-Analysis for Research and Applications (MERRA)

277   [Rienecker et al., 2011; Bosilovich et al., 2011] uses the Goddard Earth Observing System

278   Data Assimilation System version 5 (GEOS-5; Rienecker et al., [2011]) to assimilate

279   observations (e.g., radiance data) for the retrospective analyses. In the present study

280   precipitation is obtained from the latest version of the MERRA product (V 5.2) available

281   at GES DISC with resolution of 2/3° longitude by 1/2° latitude.

282

283   **2.4.3. NCEP-DOE R2**

284   The National Centers for Environmental Prediction-Department of Energy Reanalysis 2

285   (NCEP-DOE R2) product [Kanamitsu et al., 2002] uses a global data assimilation system

286   and numerical weather prediction model to produce atmospheric analyses using

287   historical data and also to produce analyses of the current atmospheric state from 1979

288   to the present. The Reanalysis-2 product fixed errors and updated parameterizations of

289   physical processes that hampered earlier versions. This product has 17 vertical pressure

290   levels globally gridded at T62 spatial resolution (~1.875°X1.875°) four times daily. Data

291   is provided by the NOAA-ESRL Physical Sciences Division, Boulder Colorado from their

292   web site at http://www.esrl.noaa.gov/psd/.

293

294   **2.5 Calculation method for precipitation characteristics**

2.5.1 Development of CloudSat gridded products

CloudSat data are transferred onto a 2.5°×2.5° grid, and the mean monthly intensity climatology is estimated by dividing the sum of all precipitation intensities for the month and grid cell by the total number of valid measurements determined as the cases in which 2c-column status_flag < 10. CloudSat is also used to provide maps of the frequency of rain occurrence, and the total number of certain precipitation retrievals is divided by the total number of valid retrievals within a grid cell. Reported precipitation frequency depends on the spatial scale, in this case reported values are precipitation frequency at the natural scale of the CPR footprint.

In each case separate maps were produced for rain, mixed-phase precipitation and snow, and these were summed to obtain total precipitation rate or frequency.

2.5.2 Calculation of regional and hemispheric precipitation rates

Total precipitation rates from each product were calculated for a number of regions including the northern hemisphere north of 55°N (NH55), southern hemisphere south of 55°S (SH55). As CloudSat only fully covers grid cells in the latitude band 80°N-S, area-mean intensities for hemispheric averages are only reported for the 55°-80° latitude bands.

In addition, the hemispheric averages were split into land and ocean and separate estimates were made for the Greenland and Antarctic ice sheets. For each product these estimates were made by multiplying the total precipitation in each grid cell by the

318 relevant area-weighted land or ocean fraction determined from the 0.125° ERA-Interim

319 land-sea mask.

320

321 **3. Results**

322 **3.1. Northern hemisphere (NH)**

323 **3.1.1. CloudSat precipitation frequency and intensity**

324 Figure 2 shows maps of annual and seasonal rain, mixed-phase, snow, and total

325 precipitation frequencies calculated using four years of CloudSat observations in NH55.

326 The first row displays the annual frequencies and the remaining rows are for

327 precipitation frequencies for each of the four seasons: winter (DJF), spring (MAM),

328 summer (JJA), and fall (OND). The map shows that snow is the most frequent land

329 precipitation type in all seasons except summer, while rain and mixed-phase

330 precipitation are more frequent over the southern part of the Atlantic Ocean, Gulf of

331 Alaska, and nearby coastal areas where daily surface temperature typically remains

332 above 0 ℃. Boreal summer precipitation mainly occurs as rainfall except in Greenland,

333 where, due to its high elevation, snowfall remains most frequent. However, rainfall and

334 mixed-phase precipitation also occur over southern coastal regions of Greenland.

335 Precipitation is most frequent over the Atlantic Ocean and Gulf of Alaska across all four

336 seasons, occurring 10-30% of the time with a summer minimum and winter maximum

337 across almost the entire region north of 55°N. As discussed in Behrangi et al. [2012],

338 precipitation frequency is sensitive to spatial scale so the values in Figure 2 should be

339 interpreted cautiously.

340

341   Figure 3 shows seasonal precipitation rates from CloudSat stratified by precipitation

342   phase. Patterns in intensity are similar to those in occurrence frequency in Figure 2,

343   except that rainfall events are consistently more intense than snow thus contributing

344   more to the total precipitation. The intense seasonal precipitation over the Atlantic

345   Ocean is mainly from rainfall and mixed phase precipitation, with the largest

346   contribution during boreal fall and winter when the Atlantic storm tracks are most

347   active.

348   **3.1.2. NH55 Annual precipitation intensity by region**

349   Figure 4 shows maps of average precipitation rates (mm/day) over NH55 constructed

350   from various products. GPCC is based on gauge observations so reports no ocean data.

351   According to CloudSat (Fig 4a), the highest precipitation rates are in the North Atlantic

352   up to the coast of Greenland and along southern coast of Alaska. This pattern is

353   qualitatively consistent with the other land-ocean products except for CMAP. GPCC (Fig.

354   4g) agrees well with CloudSat over land (Fig. 4a), but has smaller precipitation rates

355   over coastal Greenland and southern Alaska. Furthermore, GPCC has slightly higher

356   precipitation rates than CloudSat over central Canada and Eurasia. As gauges are not

357   utilized in the CloudSat precipitation estimate, its overall consistency with GPCC is

358   remarkable.   In northern Eurasia, GPCP (Fig 4b) shows a much higher mean

359   precipitation rate. GPCP and GPCC apply different correction factors to account for gauge

360   undercatch (e.g. induced by wind) which could contribute to the observed differences

361   between the two products. In Section 3.1.5 we present analysis of winter-season

362   precipitation including GRACE accumulation to support these adjustments. Over the

363   Atlantic Ocean, GPCP does not show a strong north-south gradient in mean precipitation,

while other products show a significant decrease in mean precipitation intensity poleward of approximately 70°N. GPCP displays higher precipitation intensity north of 70°N than the other products, and a lower intensity south of this band than all except for CMAP, which is a low outlier over all NH55 ocean regions. CMAP's land precipitation (Fig. 4c) is more consistent with other products, but remains the lowest. Overall, the observation-based products agree more over land than over ocean, where surface observations are non-existent. The reanalyses show less disagreement over the spatial distribution of ocean precipitation than do the observations, and MERRA and ERA-Interim are particularly consistent. NCEP-DOE R2 reports higher intensity in the Atlantic, but reports less total ocean precipitation as this is offset by less precipitation in the Bay of Alaska, North Sea and off the coast of Greenland. MERRA and ERA-Interim broadly agree with CloudSat both spatially (e.g., by reproducing the strong precipitation gradient over the Atlantic ocean from north to south of 70°N) and in terms of total ocean precipitation.

Figure 5 shows the mean and standard deviation of precipitation estimates separately for reanalysis (MERRA, ERA-interim, NCEP-DOE R2; top row) and observation (GPCP, CMAP, CloudSat; middle row) products. The bottom row is similar to the middle row, but excludes CMAP. Average precipitation is similar between observations and reanalyses over ocean when CMAP is excluded, but observations have higher variance over oceans. The large standard deviation of the satellite-gauge products over ocean is consistent with findings of Adler et al. [2012]. Note that as CMAP is the notable outlier in total ocean precipitation estimates, its removal leads to a smaller standard deviation in the observational products.

387

3.1.3. NH55 Seasonal precipitation by region

Figure 6 shows precipitation mean intensity maps of each product by season. All products report a strong seasonal cycle over both land and ocean. The Atlantic Ocean and the Gulf of Alaska receive much of their precipitation during winter and fall, while land receives more during summer. The outliers once again are CMAP, which shows suppressed amplitude of the annual cycle and NCEP-DOE R2, which shows much heavier summer precipitation over land than any other product.

As summer precipitation tends to be rain and therefore less sensitive to gauge correction factors, the gauge products should be more reliable in densely instrumented regions. For example, Bolvin et al. [2009] compared GPCP with independent gauge measurements in Finland and found good agreement. This suggests that NCEP-DOE R2 may well be overestimating land precipitation, particularly during summer.

Despite the general agreement in their seasonal patterns, the products show marked differences in total amount. Over the Atlantic south of 70°N, CloudSat reports average precipitation during fall and winter greater than 5 mm/day in many cells, exceeding CMAP and GPCP, but similar to reanalyses. Furthermore, unlike other products, GPCP does not show any noticeable precipitation gradient around 70°N over the Atlantic Ocean in any season. In winter and fall, GPCP shows much higher total precipitation than the other products over Europe, north-west Asia, and over the Atlantic north of 70°N. The observed higher estimate by GPCP over Eurasia, compared to the other products, is

410   in agreement with that found by Behrangi et al. [2014a] in which overestimation of

411   GPCP was also noticed using the net surface water exchange rate estimated from

412   remote-sensing observation and reanalysis. In the next section, this cold season

413   discrepancy is investigated in more detail by including GRACE estimates of cold-season

414   accumulation.

415

416   3.1.4. Implications of GRACE results for cold-season precipitation

417   Figure 7 compares winter estimates of snowfall from GRACE (Fig 7g) with the other

418   products over grids experiencing mean 2m air temperature below -1°C across all days in

419   winter. As described in Section 2.1, GRACE-based estimates of winter precipitation are

420   calculated from Eq. 1 using corresponding evapotranspiration and runoff values from

421   GLDAS. Note that it was found that the contributions of evapotranspiration and runoff to

422   the total precipitation are on average about 10% and 0.4%, respectively. Figure 7

423   suggests that GRACE-based seasonal accumulation of snowfall is comparable to the

424   other products, except GPCP which shows much higher total precipitation over parts of

425   northern Eurasia. This again suggests that GPCP likely overestimates precipitation in

426   this region, which could be related to overcorrection for gauge undercatch problem in

427   high latitude and especially during winter [Swenson et al., 2010].

428

429   Figure 8 compares the mean accumulated winter snowfall estimated from different

430   products, over North Asia (Fig. 8a) and North America (Fig. 8b) regions shown in Figure

431   7. The range of accumulated winter snowfall estimates is 46 mm to 64 mm (or 91 mm

432   including GPCP) in North Asia and between 34 mm and 50 mm in North America. The

433 average winter snowfall within the identified zones in North America and North Asia are

434 42.6$\pm$4.9(1σ) mm and 53.1$\pm$7.5 mm (or 58.1$\pm$ 14.6 mm including GPCP), respectively.

435 The GRACE estimate falls well within the estimated range of winter snowfall in both

436 regions and is consistent with CloudSat, MERRA, and ERA-Interim estimates.

437

438 **3.1.5. Comparison of total precipitation**

439 Figure 9 provides a summary of the 2007-2010 average annual precipitation rate and

440 spatial statistics calculated for each product over the entire NH55, NH55 oceans, NH55

441 land, and Greenland. Bar charts (top row) show mean precipitation within region by

442 products and Taylor diagrams [Taylor, 2001] show the centered spatial correlation and

443 standard deviation relative to GPCP.

444

445 These figures allow estimation of the range of precipitation estimated by observation

446 and reanalysis and the identification of key disagreements. Over NH55 the all-product

447 mean±standard deviation is 561±88 mm/yr with a range of 386—622 mm/yr. This large

448 range is due to lower estimates from CMAP, particularly over the ocean. Excluding CMAP

449 the products show substantially better agreement with mean±standard deviation of

450 596±23 mm/yr and a range of 572—622 mm/yr. Aside from CMAP, both the

451 observation and reanalysis products are fairly consistent: the maximum difference

452 between non-CMAP NH55 products is 8%, which means that observations and

453 reanalyses combined place a relatively tight bound on total precipitation amount for

454 assessment of climate models or for the precipitation component of the energy budget

455 over NH55. However, this agreement between non-CMAP products over NH55 at annual

22

456 scales hides disagreements in the spatial and temporal distribution. From the regional

457 Taylor diagrams, it can be seen that CloudSat consistently reports larger spatial

458 variability and in particular is an outlier over Greenland in terms of both total

459 precipitation (591 mm/yr versus the 300-469 mm/yr range of other products) and its

460 spatial distribution. CloudSat reports 311 mm/yr of snow and 280 mm/yr of rain and

461 mixed phased precipitation over Greenland. While the CloudSat estimate of annual

462 snowfall agrees with previous estimates of precipitation accumulation over Greenland

463 ice sheet (~300 mm/yr) using ice core, snow pits, and *in situ* measurements [Bales et al.,

464 2009; Chen et al., 2011], the intensity of rain and mixed-phase precipitation is likely

465 overestimated. We think this might be related to misinterpretation of radar backscatter

466 from the rugged topography, and thus the credibility of CloudSat rain retrievals over

467 Greenland needs to be further investigated. In particular, future revisions to the 2c-rain

468 product should include vertical continuity tests to prevent the misidentification of

469 surface clutter as precipitation.

470 Nonetheless, we identify outliers in total precipitation as those whose precipitation

471 estimate falls outside of 10 % of the range limits of the other products. From this we

472 identify CMAP over oceans in all seasons except MAM, CloudSat over Greenland in all

473 seasons except DJF, NCEP over NH55 land during JJA and GPCP over NH55 land during

474 DJF. These results are consistent with our previous identification of outliers in Sections

475 3.1.2 through 3.1.4. The Taylor diagrams in Figure 9 provide quantification of the more

476 qualitative statements made in Section 3.1.2 based on analysis of the maps.

477

478 **3.2. Southern hemisphere (SH)**

479   **3.2.1. CloudSat Precipitation frequency and Intensity**

480   Figure 10 shows maps of annual and seasonal rain, mixed-phase, snow, and total

481   precipitation frequencies calculated using CloudSat observations collected between

482   2007 and 2010. The annual frequencies are shown in the first row, followed by

483   precipitation frequencies for each of the four seasons: DJF, MAM, JJA, and SON.

484

485   Over the Antarctic continent, nearly all precipitation falls as snow and is most

486   frequent near the coasts, where its frequency of occurrence can exceed 20% in parts of

487   the Antarctic Peninsula and near some regions of the East Antarctic Ice Sheet. Away from

488   the coasts frequency of snowfall occurrence can be as low as 5% over the Antarctic

489   Plateau where elevation exceeds 2 km. The seasonal cycle of precipitation is weak over

490   the continent and stronger over the ocean, with precipitation more frequent in austral

491   summer than winter.

492

493   Over oceans the precipitation frequency is highest over the southern Pacific and Indian

494   Oceans, where it can exceed 30% during austral fall and winter. In general, the seasonal

495   variability of precipitation occurrence in SH55 (Fig. 10) is much lower than in NH55 (Fig.

496   2).

497

498   Figure 11 shows the seasonal distribution of rainfall, mixed-phase precipitation,

499   snowfall, and total precipitation rate over SH55 as observed by CloudSat. The maps

500   suggest that the intense precipitation region observed at 55°-60°S is mainly composed of

501   rainfall and mixed-phased precipitation, except in austral winter, when snowfall

502 contribution is the highest. Nearly all precipitation south of 70°S falls as snow during all

503 seasons and over both ocean and land.

504

505 **3.2.2. SH55 Annual precipitation intensity by region**

506 Figure 12 shows maps of annual average precipitation rates (mm/day) over 2007-2010

507 from CloudSat, GPCP, CMAP, MERRA, ERA-interim, and NCEP-DOE R2 for SH55. No

508 precipitation data from GPCC exists over the Antarctic continent due to the very sparse

509 precipitation gauges. The overall pattern of mean annual precipitation is consistent

510 among the studied products except for CMAP (Fig. 12c). The CloudSat precipitation map

511 (Fig. 12a) shows higher agreement with MERRA (Fig. 12d) and ERA-Interim (Fig. 12e)

512 and less agreement with GPCP.

513

514 Unlike other products, GPCP (Fig. 12b) does not show significant longitudinal variation

515 in precipitation intensity along the band between 55°-60°S and shows continuous

516 annual precipitation intensity of greater than 3mm/day in this zone. This is consistent

517 with previous findings indicating that GPCP overestimates zonally averaged

518 precipitation rates around 60°S (Behrangi et al. 2014). Figure 12c shows that CMAP

519 consistently underestimates precipitation rates and has wide areas of missing data over

520 the ocean south of 60°S (shown in white).

521

522 NCEP-DOE R2 consistently reports higher precipitation intensity than MERRA or ERA-

523 Interim, with a continuous band of heavier precipitation heading equatorward from the

524 Antarctic Peninsula that is not seen in ERA-Interim, MERRA or CloudSat. NCEP-DOE R2

525 also reports more intense precipitation on the periphery of Wilkes Land, and

526 penetrating more deeply into the continent from the Bellingshausen and Amundsen Seas

527 than is seen in other products. CMAP reports rates of order 1 mm/day inland from the

528 Ronne Ice Shelf to Queen Maud Land, and some larger precipitation rates at the edge of

529 Kaiser Wilhelm II Land that are not seen in other products.

530

531 Figure 13 shows mean and standard deviation of precipitation estimates, calculated

532 separately from reanalyses (MERRA, ERA-interim, NCEP-DOE R2; top row), and

533 observations (GPCP, CMAP, CloudSat; middle row) over SH55. The bottom row is similar

534 to the middle row, but excludes CMAP from calculations. Consistent with NH55 (Fig 5),

535 reanalyses show higher agreement among themselves than with observations, especially

536 over ocean. Removing CMAP suppresses the spread in observational estimates and leads

537 to regional patterns that are more similar to reanalyses.

538

539 **3.2.4. SH55 Seasonal precipitation intensity by region**

540 Figure 14 shows seasonal distribution maps of precipitation mean intensity for the

541 products for SH55. All of the products (except CMAP) suggest a seasonal variation that is

542 not as strong as that observed for NH55 (Fig. 6). The products agree that the Southern

543 Ocean receives much of its precipitation during austral fall and winter. Figure 14 shows

544 that the GPCP's continuous zonal band of intense precipitation around 60°S (observed in

545 Fig. 12) is observed across all four seasons, but is more distinct in austral fall. In

546 particular, there appears to be a discontinuity in GPCP's reported precipitation

547 intensities at 60°S that is most obvious in austral summer and fall.

548

Over West Antarctica and the Antarctic Peninsula, ERA-Interim is most similar to GPCP and CloudSat throughout the year while MERRA reports more intense local precipitation from austral fall through spring. NCEP-DOE R2 consistently shows more widespread snow and continues to report widespread snow during austral summer over the West Antarctic coast up to where it meets the Ross Ice Shelf, where other products report little or none.

555

3.2.5. Comparison of total precipitation

Figure 15 is similar to Fig. 9, but is over SH55, SH55 ocean, and SH55 land (Antarctica). Once again, CMAP is a notable low outlier at 303 mm/yr that is mainly related to underestimation over ocean. Excluding CMAP the products show mean±standard deviation of 667±46 mm/yr and a range of 611—732 mm/yr. Based on CloudSat data, precipitation totals are split by phase as follows: snow 50.1%, rain 13.7% and mixed-phase 36.1%. CloudSat is not an outlier over Antarctica as it is over Greenland, perhaps because the challenges with retrieval of rainfall are not relevant in Antarctica (see Figure 10).

565

Over Antarctica, CloudSat reports 178 mm/yr of snowfall, accounting for approximately 97.5% of total precipitation. We consider this to be consistent with the 171 mm/yr by Palerme et al. (2014). The remaining 4 % difference may be explained by different time periods (2007—2010 here versus August 2006 to April 2011 in Palerme et al. [2014]), regional coverage (north of 80 °S here, north of 82 °S in Palerme et al. [2014]) and

571 potentially choice of land-sea mask. This result is also similar to the ~ 170mm/yr

572 estimate by Vaughan et al. [1999] who interpolated between a compilation of in situ

573 surface accumulation measurements throughout Antarctica.

574

575 Among the reanalyses, ERA-Interim is closest to the observations with 193 mm/yr of

576 total precipitation, while MERRA and NCEP-DOE R2 report 23-37 % more snowfall. It

577 has been reported that ERA-Interim does not show temporal discontinuities over

578 Antarctica and likely presents the most realistic depiction of changes in Antarctic

579 precipitation over 1989-2009 [Bromwich et al., 2011]. ERA-Interim is also in stronger

580 agreement with CloudSat estimates in terms of both total precipitation and their spatial

581 statistics shown in the Taylor diagram.

582

583 Figure 15 implies that CMAP is a consistent outlier over both land and ocean, both in

584 terms of absolute precipitation and spatial distribution. Meanwhile, over oceans GPCP

585 displays larger spatial variability than other products, in terms of the centered standard

586 deviation, which is consistent with the latitudinal discontinuity (see Fig. 12). The

587 clustering of the reanalyses and CloudSat on the Taylor diagram for SH55 ocean suggests

588 better agreement between these products in the spatial distribution of precipitation.

589 Unlike in NH55 where we were able to find evidence suggestive of reasons for outliers

590 (GPCP gauge correction and CloudSat 2c-rain topography issues), we are not able to

591 identify clear reasons for the magnitude of this spread. As such, it appears that our best

592 estimates from observation and reanalysis of SH55 precipitation span a larger range

593   than over NH55, with a maximum difference depending on product choice of 18 %,

594   versus 8 % in NH55.

595

596   **4. Concluding Remarks**

597   Precipitation estimates from ground observation (GPCC), remote sensing (GPCP, CMAP,

598   CloudSat, and GRACE), and reanalyses (MERRA, ERA-Interim, and NCEP-DOE R2) are

599   compared in terms of total annual and seasonal precipitation in high-latitude regions

600   between 55°-80° latitude. Additionally, CloudSat precipitation products are used to

601   characterize the frequency of precipitation occurrence and precipitation phase. The

602   period 2007-2010 was selected as this is when CloudSat provides a complete

603   observation record. CMAP, GPCP and GPCC utilize gauges over land, CloudSat is very

604   sensitive to light rain and snowfall, and GRACE enables a fully independent estimation

605   (i.e. gravimetry versus radiometry) of accumulated cold-season precipitation.

606

607   Overall, a fairly good agreement between CloudSat and GPCP is found in total annual

608   precipitation across the domains studied, with differences of <10% absolute over NH55-

609   land-ocean, NH55-ocean, SH55 and SH55-ocean while results are almost identical over

610   Antarctica. However, these totals mask regional and seasonal differences. For example,

611   CloudSat reports much heavier total precipitation over Greenland, which is attributed to

612   surface radar returns over rugged topography being misinterpreted as intense rain.

613   GPCP reports much heavier winter precipitation over northern Eurasia, which is

614   attributed to a likely issue with gauge correction factors. GPCP also differs from other

615   products over the Atlantic Ocean where it does not show a distinct latitudinal gradient in

616　precipitation on either side of 70°N, and over the Southern Ocean where there is a

617　notable discrepancy in precipitation rates at 60°S. CMAP is a clear outlier over the

618　oceans, with total precipitation 50% lower than the mean of the other products in NH55

619　and 30% lower in SH55. Over land it also provides the lowest estimate but is less

620　extreme as an outlier, likely due to its use of ground gauges for bias correction.

621

622　Among the reanalyses, over NH55 MERRA and ERA-Interim are generally consistent

623　with each other on large spatial scales while NCEP-DOE R2 reports about 20% more

624　precipitation over land. The most obvious contributor to this higher estimate is high

625　accumulation during summer. As this is the warm season when land precipitation is

626　predominantly rain, undercatch uncertainties are smaller, so products utilizing gauge

627　networks (e.g., GPCP) are more likely to be reliable. MERRA and ERA-Interim are more

628　consistent with the gauge estimates, suggesting that NCEP-DOE likely overestimates

629　land precipitation in NH55, particularly during boreal summer. In SH55, reanalyses are

630　approximately evenly spread over the range 611—732 mm/yr, with ERA-Interim the

631　lowest and NCEP-DOE R2 the highest. NCEP-DOE R2 is the furthest from CloudSat over

632　the ocean (13% higher) and especially over Antarctica (44% higher), whereas ERA-

633　Interim most closely matches the CloudSat and GPCP observed totals. Considerable

634　seasonal variation is seen in SH55 precipitation maps, but this is weaker than in NH55.

635　All products agree that SH55-ocean receives much of its precipitation during austral fall

636　and winter. Antarctica has a weak seasonal cycle with a minimum in winter. CloudSat

637　reports that precipitation south of 70°S is almost purely from snowfall across all seasons

638　over both ocean and land. In general, the CloudSat and re-analysis (MERRA and ERA-

639 Interim) results agree well with each other, both in terms of absolute magnitude and

640 pattern in most areas and this cross-confirmation increases our confidence in their use.

641 The merit of reanalysis to produce precipitation fields in middle to high latitudes (e.g.,

642 Adler et al. [2001]) is likely due to large-scale dynamics and moisture convergence

643 playing a dominant role in precipitation processes and the success at assimilating

644 conventional and satellite temperature and moisture soundings.

645

646 We find that some regional discrepancies remain between precipitation products, which

647 suggest locations where they should be used cautiously. For rain over the oceans and

648 snow over all surfaces, for which the 2c-rain and 2c-snow algorithms were designed,

649 GPCP, MERRA and ERA-Interim tend to be consistent with CloudSat totals although the

650 GPCP spatial distribution of rainfall over the ocean is not in good agreement. Over NH55

651 land where gauge data is used, MERRA and ERA-Interim also agree better with the

652 gauge-based products than does NCEP-DOE R2. Over Antarctica, ERA-Interim is in best

653 agreement with both GPCP and CloudSat.

654

655 Issues of concern raised by this intercomparison are that NCEP-DOE R2 reports much

656 higher summer precipitation over land in NH55 than all other products, that GPCP

657 reports excess snowfall over northern Eurasia, and that CMAP consistently reports much

658 less precipitation over oceans. The quality of CloudSat rain estimation over Greenland

659 also remains a subject for further investigation.

660

661   Although precipitation estimation at higher latitudes is a major challenge that has not

662   been fully addressed by the Earth observing community, we show in this paper that

663   some progress has been achieved. This is indicated by the level of agreement between

664   products derived from independent data sources. The present comparative analysis

665   provides useful insights for diagnostic assessment of precipitation products in high

666   latitudes, quantifying uncertainties among observations and reanalyses, and establishing

667   a benchmark for assessment of climate models. The recently launched Global

668   Precipitation Measurement (GPM) mission [Hou et al., 2014] deploys a Ka/Ku band dual

669   frequency precipitation radar (DPR) and a multichannel passive microwave imager

670   (GMI) on its Core Observatory, covering 65°S-N. The higher sensitivity of GPM core

671   instruments to light rain and snowfall, extended coverage (compared to 35°S-N for

672   TRMM), and improvements in precipitation retrieval methods provide unprecedented

673   opportunities to take on the challenges of quantifying light rain and falling snow. The W-

674   band radar on CloudSat has snow detection thresholds more than an order of magnitude

675   lower than the GPM radars [Skofronick-Jackson et al., 2013], suggesting that CloudSat is

676   highly complementary to the existing suite of spaceborne sensors, especially over high

677   latitudes where light precipitation is dominant. The occurrence of a battery anomaly in

678   April 2011 significantly reduced CloudSat's battery capacity. The issue was mitigated by

679   reconfiguring the spacecraft's operations to what is referred to as the Daylight-Only

680   Operations (DO-Op) mode in which CloudSat makes radar measurements for ~56% of

681   each orbit, while the sensitivity of the radar remains essentially unchanged. Successful

682   operation of the DO-Op mode since 2011 suggests a mission life with reasonable

683   likelihood of operations through 2019 (CloudSat Senior review 2015). Further near-

684   future W-band observations are expected with the future launch and operation of the

685   Earth, Clouds, Aerosols and Radiation Explorer (EarthCARE) mission [Illingworth et al.,

686   2015].

687

688   It is also hoped that comparative analysis over short periods at high latitudes using

689   CloudSat such as in this study and soon GPM will enable adjustments or corrections to

690   the remote sensing and analysis techniques utilized to produce long-term global

691   analyses such as GPCP. Thus these recent observations will help enable a more accurate

692   and consistent picture of the long-term precipitation climatology and inter-annual and

693   inter-decadal variations back through the satellite era.

694

695

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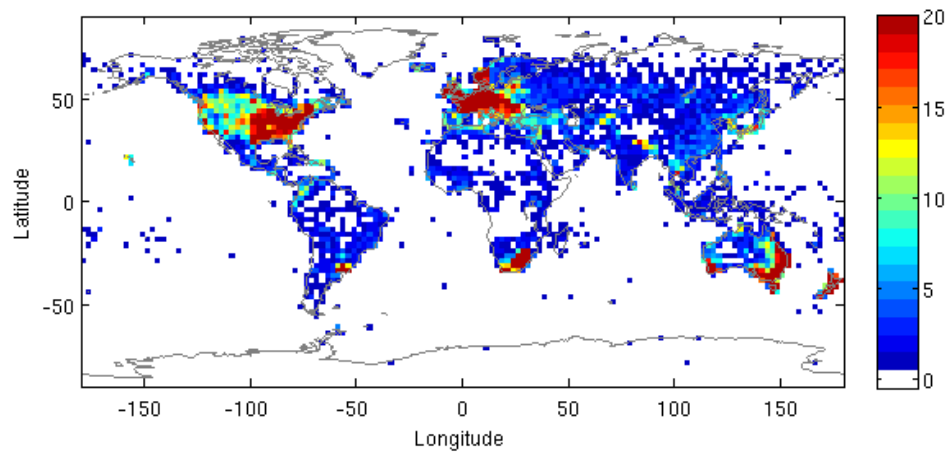
Figure captions:

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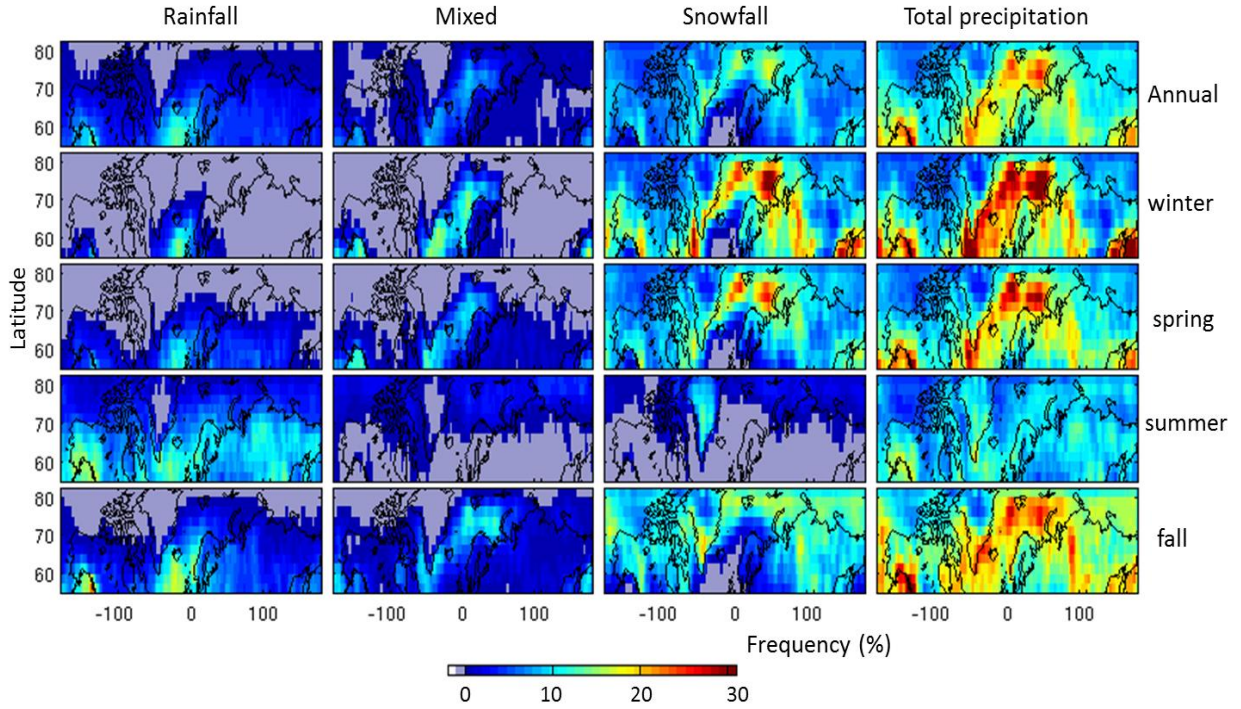
Figure 2. Maps of annual and seasonal rain, mixed-phase, snow, and total precipitation frequencies calculated using four years of CloudSat observations poleward of 55°N. The first row displays the annual frequencies and the remaining rows are for precipitation frequencies for each of the four boreal seasons: winter (DJF), spring (MAM), summer (JJA), and fall (OND).

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Figure 4. Maps of four-year averaged precipitation rates (mm/day) for 2007-2010 constructed from CloudSat, GPCP, CMAP, MERRA, ERA-Interim, NCEP, and GPCC over land and ocean north of latitude 55°. White areas represent missing or non-reported data.

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Figure 9: Precipitation statistics for each product by region. Top row: bar charts show mean precipitation (2007-2010) within region by product, organized as reanalyses (left 3 bars) and observations (right bars). The red solid bar shows the mean ±1 standard deviation of the reanalysis product means, the dashed black bar shows the mean ±1 standard deviation of the observational series GPCP, CMAP and CloudSat, and the solid black bar is the same excluding CMAP. Bottom row: Taylor diagrams of the same regions, product symbols shown in legend (far right) and the reference (black star) is the mean of

the reanalyses plus the geographically complete observations GPCP and CloudSat. Regions are, from left to right: the entire NH (55-80ᵒN), NH oceans (55-80ᵒN), NH land (55-80ᵒN), and Greenland.

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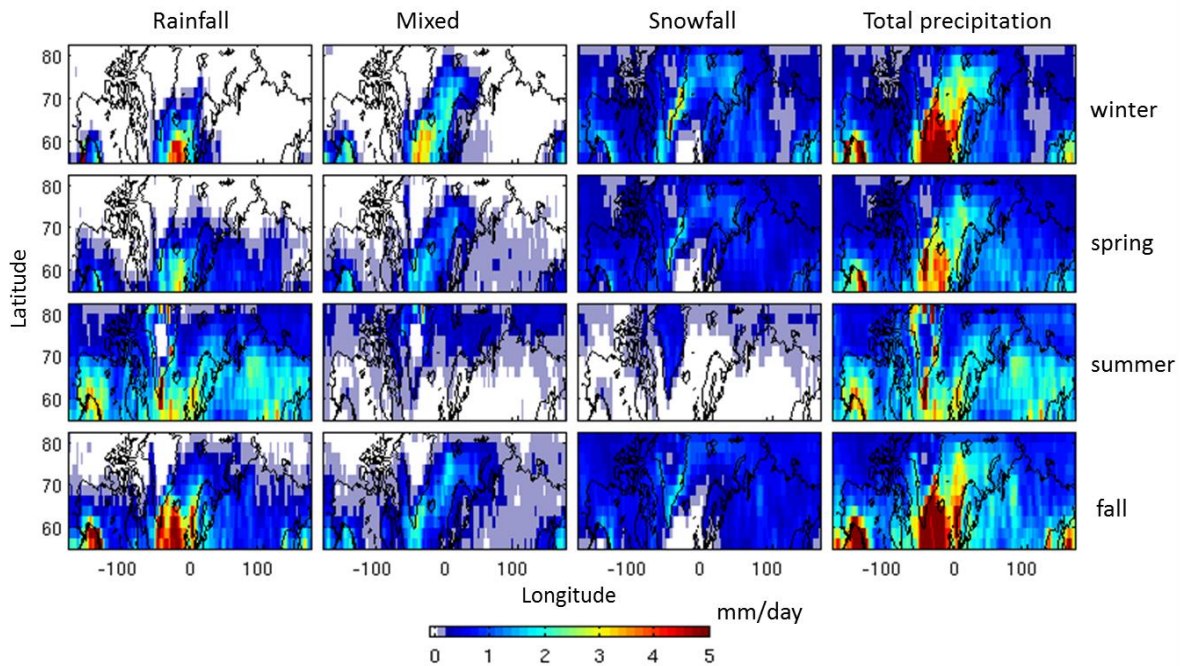
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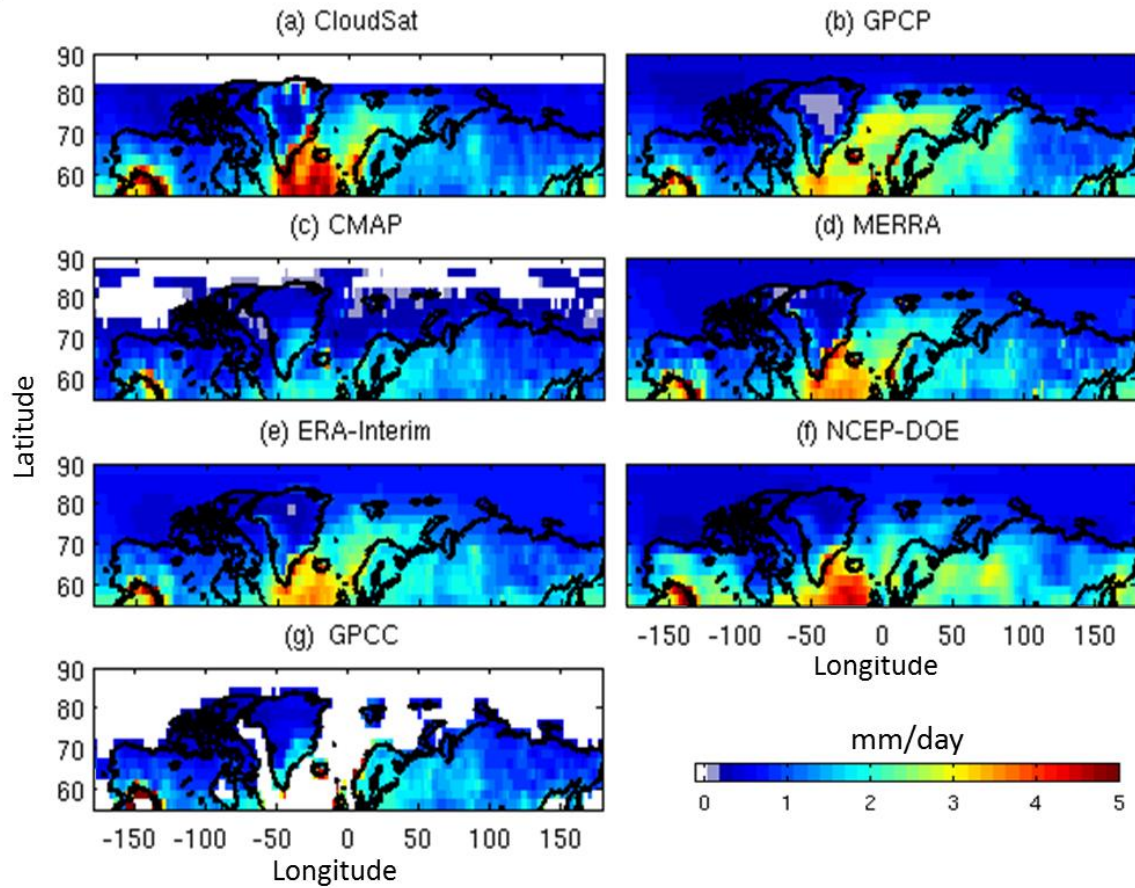Figure 12. Maps of 2007-2010 averaged precipitation rates (mm/day) constructed from CloudSat, GPCC, GPCP, CMAP, MERRA, ERA-interim, NCEP, and GLDAS over land and ocean south of latitude 55°. White areas represent missing or non-reported data.
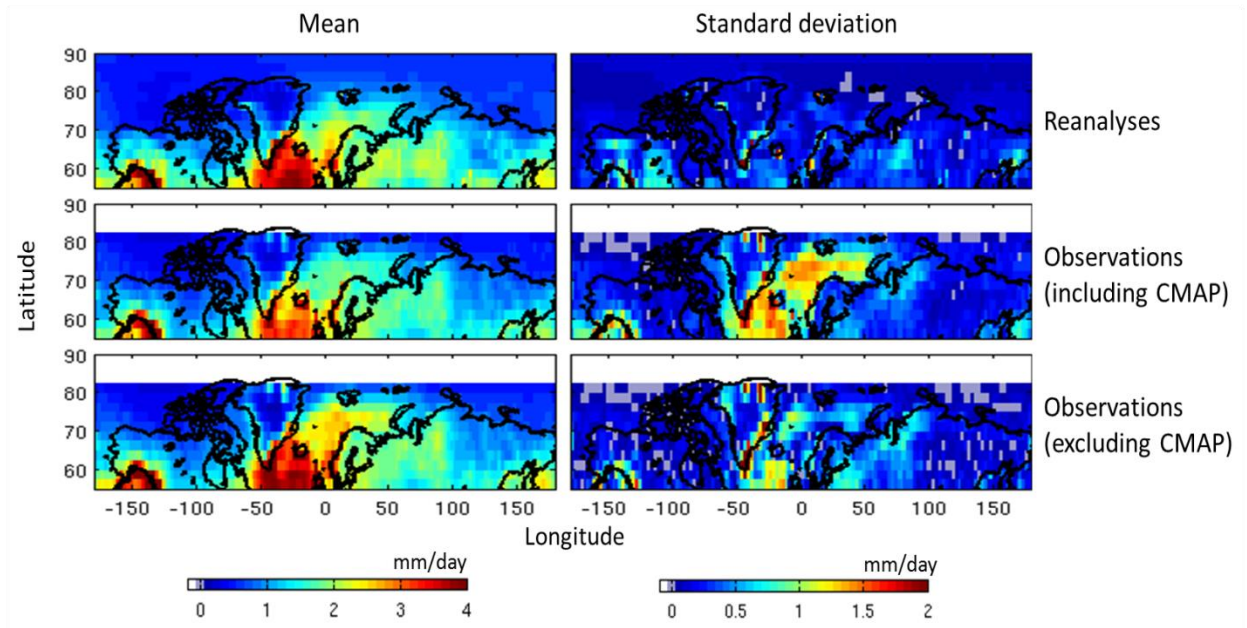
Figure 13. Maps of mean and standard of precipitation estimates, calculated separately for reanalysis (MERRA, ERA-Interim, NCEP; bottom row) and observation (GPCP, CMAP, CloudSat) products in SH for 2007-2010.
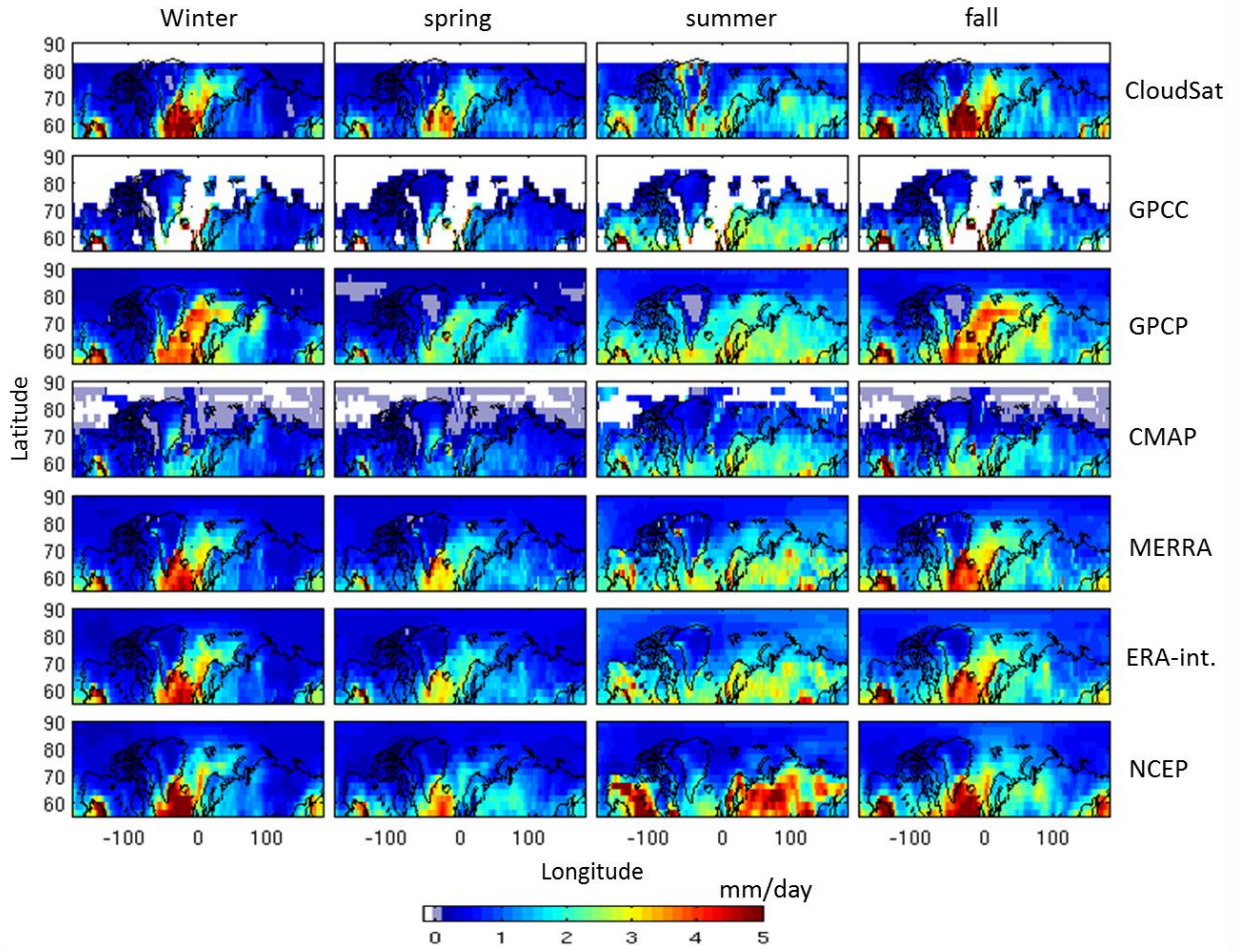
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Figure 15. Similar to Fig. 9 but for Southern Hemisphere 55-80° (SH55). Regions are, from left to right: the entire SH (55-80ᵒS), SH oceans (55-80ᵒS), and SH land (55-80ᵒS)(Antarctica). GPCC has no data over Antarctica and is not shown.

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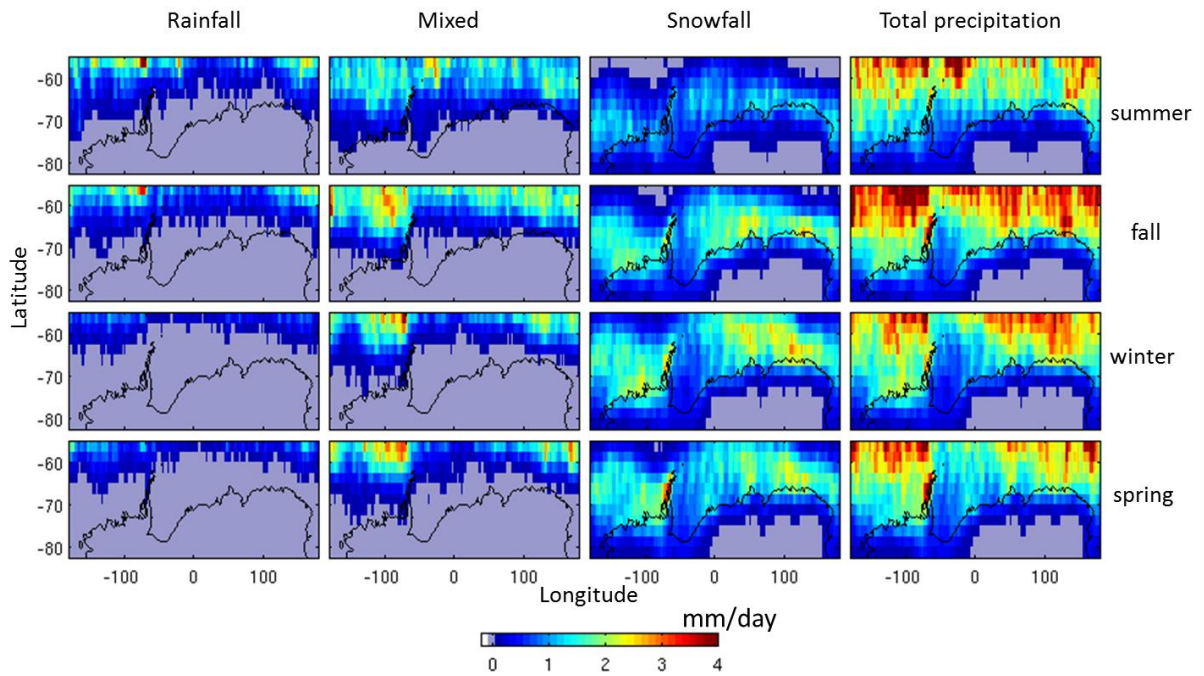
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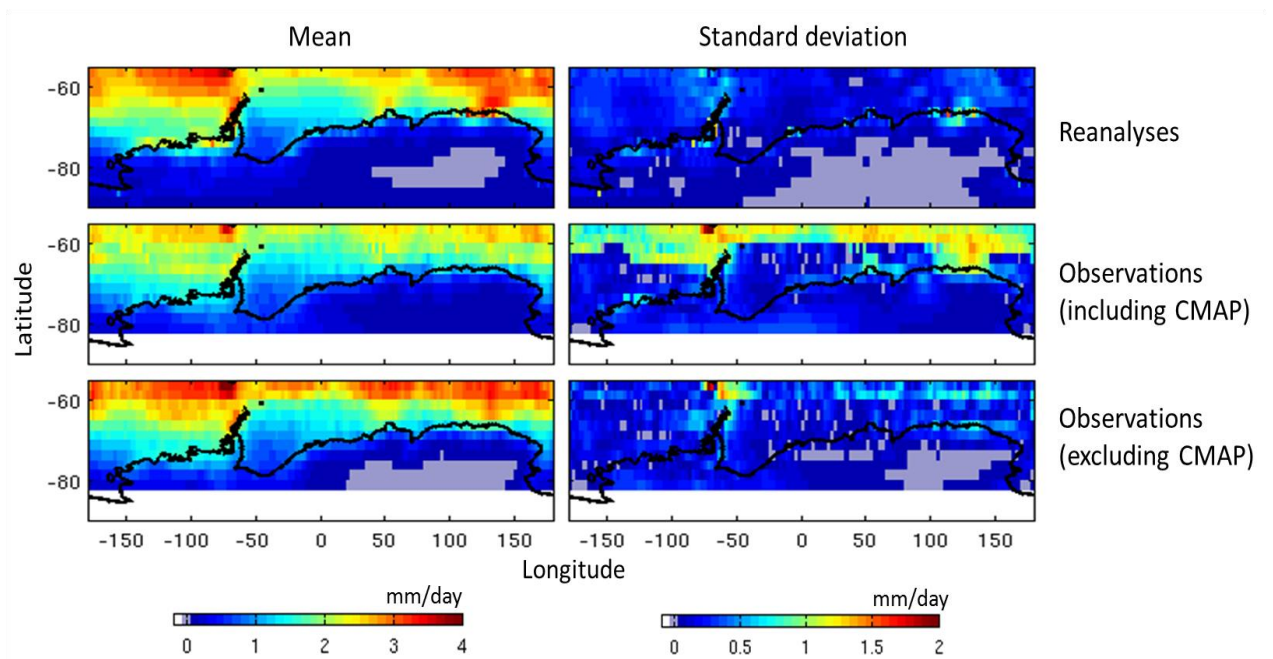
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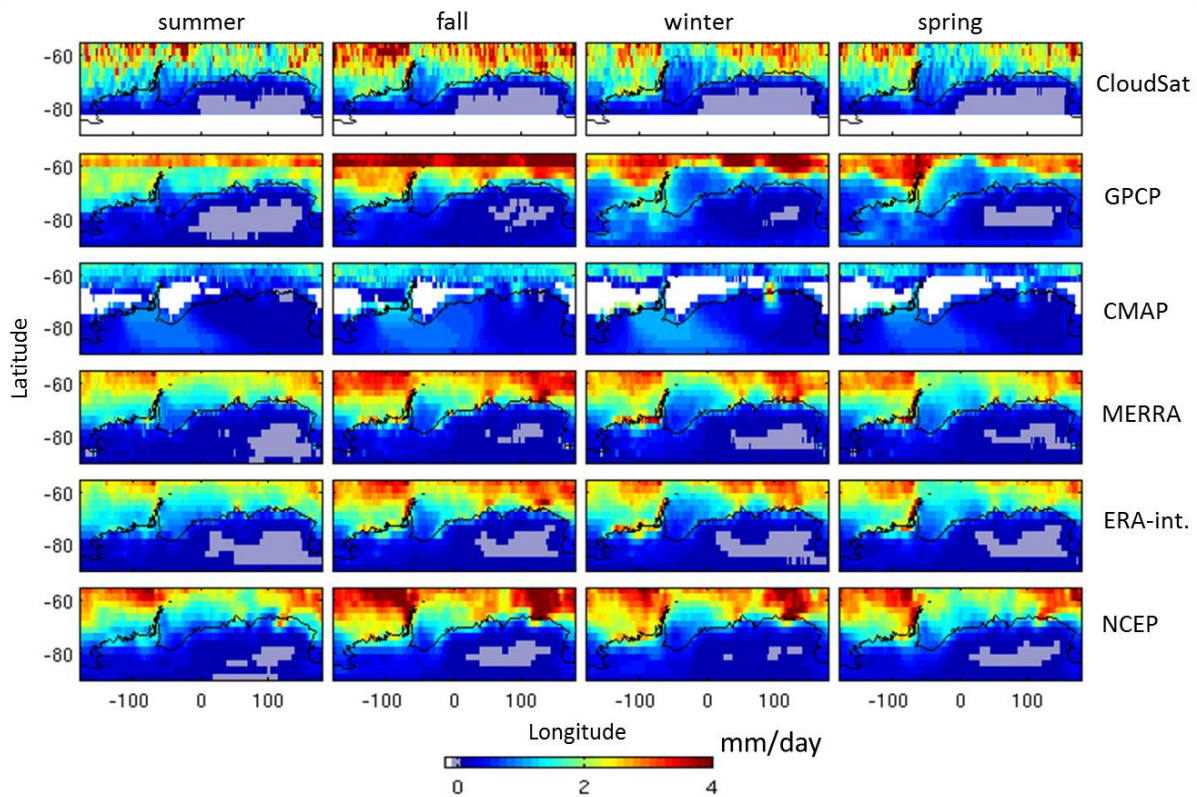
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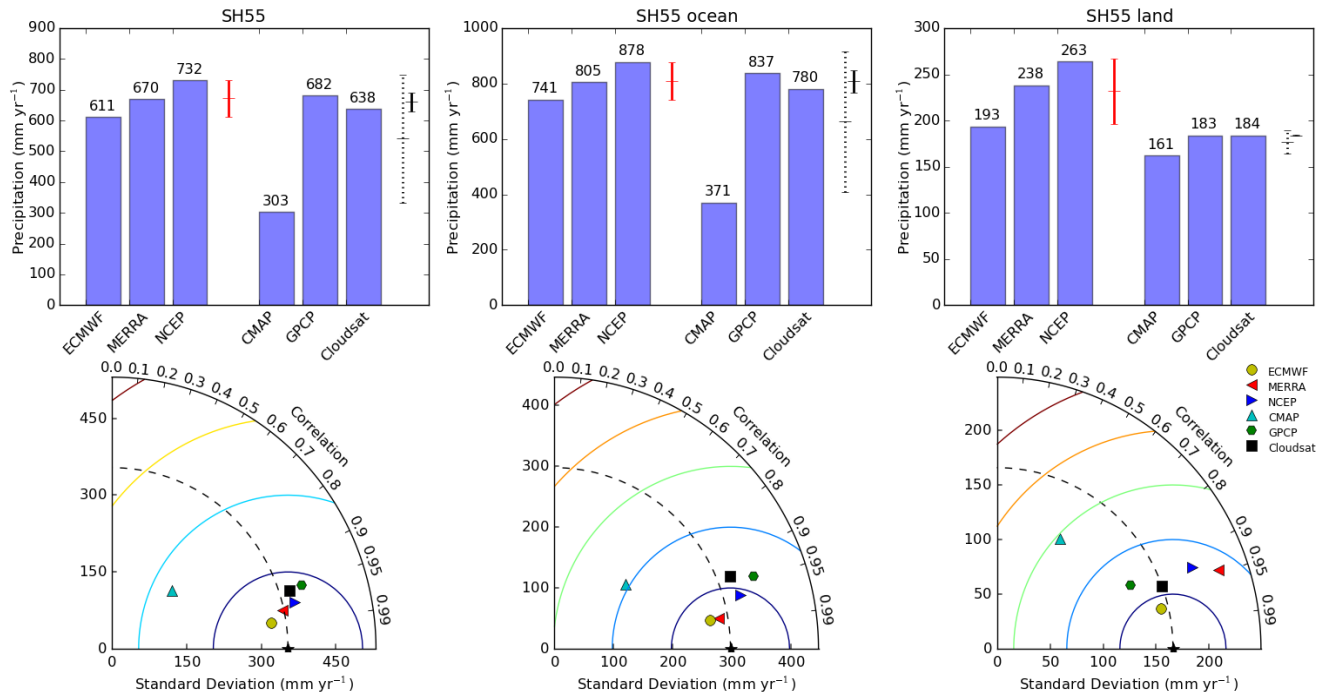
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